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THE PHASE ANGLE OF NORMAL HUMAN SKIN

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Gildemeister [1928], Einthoven & Bijtel [1923] and Hozawa [1932] have measured the resistance and capacity of human skin in the audio-frequency range. The calculated phase angles show a decreasing

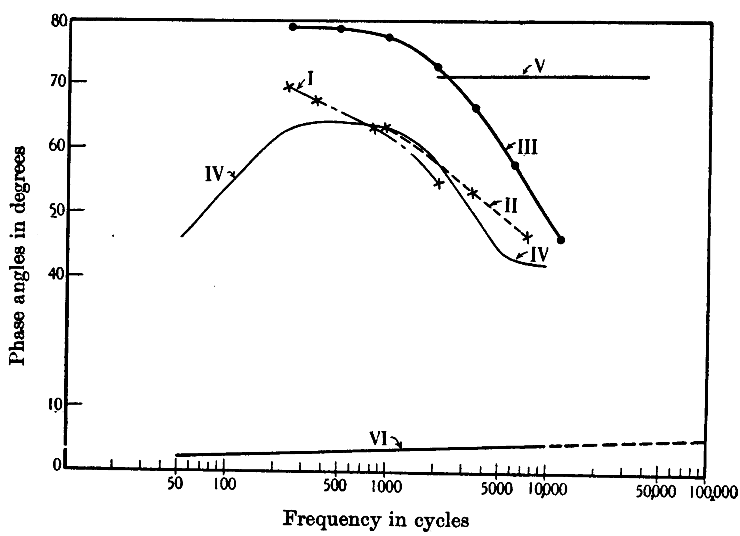


Fig. 1. Phase angle of the skin and deep tissues as a function of frequency according to various authors. I, Gildemeister; II, Einthoven & Bijtel; III, Hozawa; IV, Horton & van Ravenswaay; V, Present author; VI, Solid line, Horton & van Ravenswaay; dotted line, present author. Curves I–V refer to the skin, curve VI to the inner impedance (deep tissues).

characteristic with increasing frequency (Fig. 1). Cole [1932] has shown that, for biological materials as diverse as potato, frog nerve, rabbit muscle and frog skin, the impedance may be represented over a very wide frequency range by either one of two simple networks (Fig. 2*a*) containing two resistances and a single variable impedance element of constant phase angle. From the existing data on human skin, this author [1933] has calculated the phase angle of the variable impedance element and finds that, whereas the measurements of Gildemeister and Einthoven & Bijtel give a value of about 55°, those of Hozawa run as high as 89–90°. Cole suggests that this wide divergence may be due to some systematic error in the bridge technique of the earlier authors. However, since precise experimental procedures for separately measuring the properties of the skin and of the underlying tissues were not available to any of these workers, it is not unlikely that the estimated effect of the deep tissues on the skin measurements may have been grossly at fault.

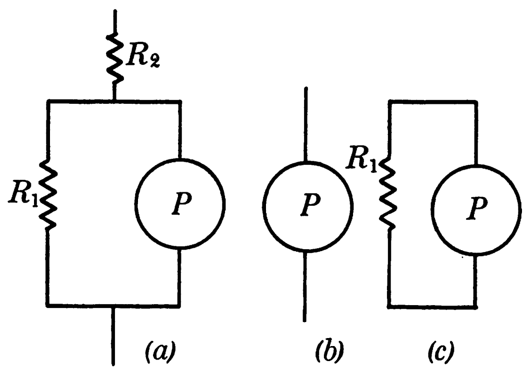


Fig. 2. Networks representing the electrical properties of various biological materials and normal human skin. (*a*) Circuit containing a variable polarization impedance P of constant phase angle and representing the properties of certain biological materials. (*b*) Circuit representing the impedance properties of the skin over a limited frequency range; element P as in (*a*). (*c*) Circuit representing the properties of the skin from zero to 40,000 cycles.

The recent development of a four electrode method by Horton & van Ravenswaay [1935] for separately measuring the impedance components of the skin ("surface sheath") and of the deeper tissues ("inner impedance") permits an entirely new approach to this problem. The experimental principle employed by these authors is the one embodied in the Kelvin double bridge [Hague, 1932] which is also a four terminal network. It will be recalled that this bridge was designed to avoid errors due to imperfect contact at the bridge arm terminals in measuring resistances of small value. This was accomplished by the simple stratagem of tapping off voltages across the terminals of the resistor under test and balancing these voltages, the effect of any contact resistance being thus eliminated. Although the original Kelvin double bridge was designed for use with direct current, a number of A.C. bridges have since been developed embodying the same principle [Hague].

In applying the double bridge principle to body measurements, Horton & van Ravenswaay use a first pair of electrodes A–C (Fig. 3*a*) encircling the wrists or forearms as current terminals. The impedance

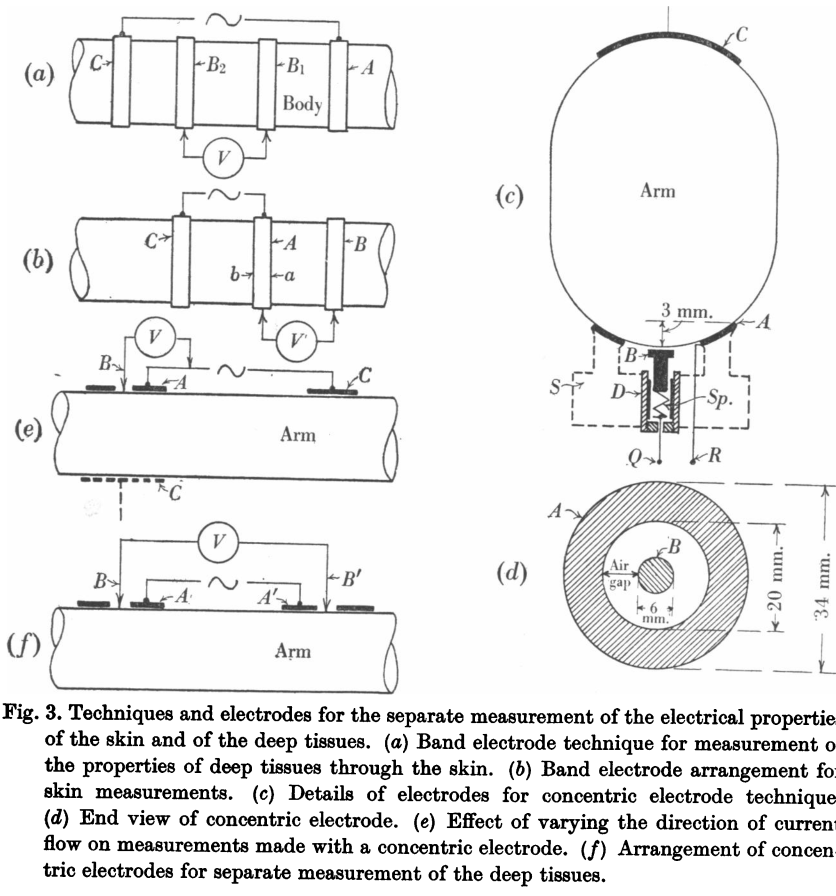


Fig. 3. Techniques and electrodes for the separate measurement of the electrical properties of the skin and of the deep tissues. (*a*) Band electrode technique for measurement of the properties of deep tissues through the skin. (*b*) Band electrode arrangement for skin measurements. (*c*) Details of electrodes for concentric electrode technique. (*d*) End view of concentric electrode. (*e*) Effect of varying the direction of current flow on measurements made with a concentric electrode. (*f*) Arrangement of concentric electrodes for separate measurement of the deep tissues.

properties of any portion of the body lying between these terminals such as the upper arm or chest may then be measured by tapping off voltages from a second pair of electrodes B_1–B_2 positioned to delimit the body segment being studied. Since the voltages tapped off in this way are independent of contact impedance, the effect of the skin is eliminated and the results obtained represent the properties of the deep tissues or "inner impedance" alone. If it be desired to study the properties of the skin or "surface sheath", one voltage is tapped off at one of the current terminals such as A (Fig. 3*b*) and the other at some external point B. From reactance and resistance measurements made with an A.C. comparator either the Q-factor or the phase angle of the skin may be calculated. The curve shown in Fig. 1 represents the phase angle values calculated from the data of these authors over the frequency range 50–10,000 cycles. Above 500 cycles, it has the same general form as those of previous workers (decreasing values with increasing frequency).

As will be shown further on, the band electrode set-up of Horton & van Ravenswaay is not an ideal one for measuring the phase angle of the skin since edges a and b of electrode A (Fig. 3*b*) are at a different potential with respect to voltage tapping electrode B. For the sake of greater rigour, the concentric electrode arrangement shown in Figs. 3*c* and 3*d* was therefore adopted. Here, electrode A is made in the form of a small annulus and voltage-tapping electrode B is mounted in the centre thereof. The voltage-tapping electrode being within the boundaries of the current-carrying electrode and at a constant distance from its limiting edges, errors due to voltage gradients are reduced to a minimum. Using this concentric electrode, the phase angle of normal skin has been measured by two independent methods. They will be designated as "Direct" and "Indirect".

Direct method

In this method, the phase angle of the skin is measured directly with a phasemeter.

The measuring instrument. This differs considerably from the A.C. comparator of Horton & van Ravenswaay and is a special phasemeter described in a previous paper [Barnett, 1935] slightly modified for use with a four-terminal network. It is composed of phase-changing (Fig. 4) and phase-indicating units in all respects identical with those originally used and which need not be described again here. The number of terminals employed, however, is increased from two to three. Current is fed to the body between terminals 1 and 2 (ground) which are in series with a large resistance, and voltages are tapped off between terminals 3 and 2. The grounded current and voltage terminals being common, the four-terminal network is reduced in effect to a three-terminal system. Measurements were made at 15,300 c./sec. using a wattmeter as a null instrument and at 11,200 and 41,800 c./sec. with a cathode ray type of instrument. The phase angle indication in these phasemeters is read off directly from a phase changing dial P and remains independent of the impedance. Measurements made on impedances of known value showed the accuracy of the instrument to be within 1 p.c. By short-circuiting terminals 2 and 3, the phasemeter may be converted into the two-terminal instrument previously described.

The electrodes. These are shown in Figs. 3*c* and 3*d* and are of two types, concentric and simple. Concentric electrode A–B consists of (1) a monel metal annulus A covered with outing flannel and bent into cylindrical form (the curvature of the annulus is indicated in the drawing) to fit the upper arm and (2) a carbon voltage tapping electrode B measuring 6 mm. in diameter at the contact end and provided with a bronze spring Sp tending to force the electrode into contact with the skin. Electrode A measures $34 \times 20 \times 1{\cdot}0$ mm. and has a total surface area of 6 cm.[2] Elements A and B are mounted together on a hard rubber support S and make separate connexion to terminals Q and R, all junctions being soldered including the one to the monel metal annulus. Electrode B is a brush holder taken from a Bodine Electric Co. Type C-3 motor and consists of a brass-lined hard rubber shell D fitted with a bronze spring Sp. Electrodes A and B should be mounted above the level of their support to leave an insulating air gap. This may be done conveniently by seating annulus A in a wax bed.

Simple electrode C is a monel metal disc, 34 mm. in diameter $\times 1{\cdot}0$ mm. also covered with outing flannel and mounted on an appropriate hard rubber support. It is immaterial

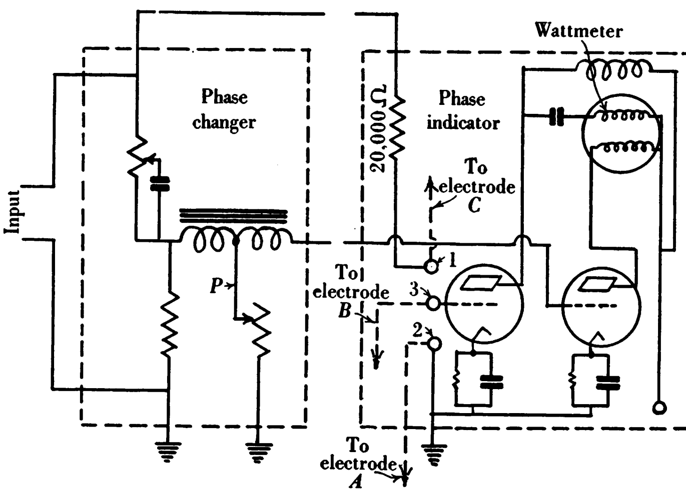


Fig. 4. Direct reading phasemeter for use in three- and four-electrode techniques.

whether this electrode be flat or bent, since perfect contact with the skin is unnecessary. The contact impedance of electrode A wetted with 1 p.c. saline and applied flat to a copper plate was found to be 0·5 ohm at 15,300 c./sec. and the phase angle of this system in series with a pure resistance of 100 ohms, 0·004 radian.[1]

Measuring technique. The skin is first gently wiped with acetone and permitted to dry and return to normal temperature. Electrodes A–B and C are then soaked in 1 p.c. saline and mounted by means of rubber bands on opposite sides of the upper arm (Fig. 3*c*), electrode A–B lying over the triceps and C over the biceps. Current is fed to electrodes A and C from the phasemeter and passes transversely through the arm, voltages being tapped off between electrodes B and A. Annulus A, it will be noted, serves as ground for both the current supply and voltage. With the electrodes in position, it suffices to rotate the phase changing dial of the phasemeter until the wattmeter or cathode ray tube indicates a null to

[1] The impedance of the skin area lying below annulus A is about of the order of this resistance in normal individuals. The phase angle value thus found represents the correction to be applied to the total phase reading taken as described further on.

obtain a phase reading. In making these readings, it will be observed that, during the first minute or two that the electrodes are in place, the phase angle gradually increases. This appears to be due to the diminution in contact resistance during the time that the saline is penetrating the epidermis. At the end of about a 2 min. period the phase angle becomes constant and repeated readings made thereafter give the same value. It is the final stable reading which is taken as representing the true phase angle of the skin. Phase angle determinations made in this way are reproducible to within $\pm 1{\cdot}0°$. All measurements, unless otherwise indicated, were made at 15,300 c./sec.

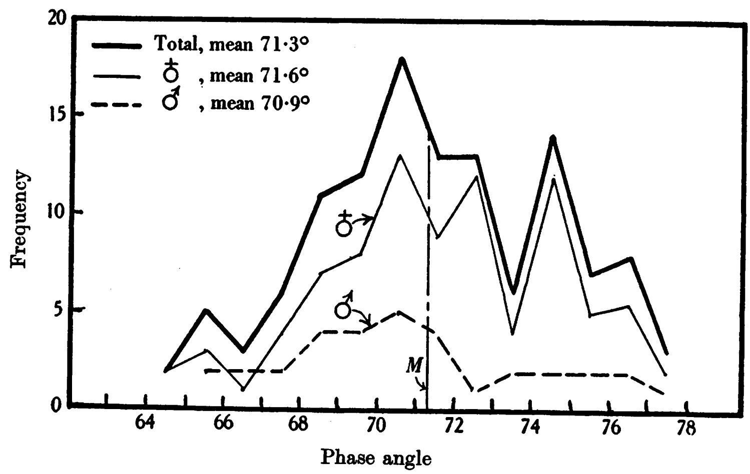


Fig. 5. Frequency polygon of normal phase angle values for 120 subjects; 87 females, 33 males.

Results. A number of initial readings made on two normal subjects showed values of 65° for one and 74° for the other. This appeared to indicate that the normal values extended over a considerable range and that, in order to find the limits of this range and determine its distribution, it would be necessary to make measurements on a relatively large number of individuals. Through the courtesy of Dr C. V. Bailey, 120 normal subjects (87 females and 33 males) undergoing a general physical examination were made available for study.

The results obtained are shown in Fig. 5. The phase angle of the skin was found to vary between 64° and 78° for different individuals with a mean value of 71·3° and a standard deviation of 2·85°. There is no significant difference between the distributions for males and females.

In eight unselected subjects (four males and four females) having an average phase angle of 72·5°, phasemeter readings were made at all three frequencies available, i.e. at $11{\cdot}2\times10^3$, $15{\cdot}3\times10^3$ and $41{\cdot}8\times10^3$ c./sec. The results in all cases showed constancy with frequency to within $\pm 1^\circ$.

Indirect method

Fricke [1932] has shown that, for a polarization impedance, if the polarization capacity varies as an inverse power function of the frequency, i.e. if the log (capacity)-log (frequency) curve is a straight line, the phase angle of the polarization impedance is constant and may be calculated from the following relations:

$$C_p = \text{const.} \times f^{-m}, \qquad \text{......(1)}$$

$$\psi = m \,.\, \pi/2, \qquad \text{......(2)}$$

where C_p is the polarization capacity, f the frequency, ψ the complement of the phase angle, and m a constant (slope of the straight line obtained from the log log plot).

From equations (1) and (2) it follows [Cole, 1934; Murdock & Zimmerman, 1936] that

$$z = \text{const.} \times f^{-\alpha}, \qquad \text{......(3)}$$

$$\phi = \alpha \,.\, \pi/2, \qquad \text{......(4)}$$

where z is the impedance, ϕ the phase angle and α a constant having the value $1-m$ (equation (1)).

For a condition of constant phase angle, a log log plot of impedance against frequency should, therefore, also give a straight line of slope α.

Inasmuch as the impedance of the 6 cm.^2 skin area under electrode A may be determined with the same arrangement of electrodes used for measuring the phase angle, it was considered to be of interest to make impedance readings at a number of frequencies (1) to determine with certainty that a constant phase angle condition existed above 11,000 c./sec., (2) to check the absolute values found by the direct method and (3) to obtain data at frequencies below 10,000 c./sec.[1]

Since it would be impracticable to measure impedances over a frequency range in as large a number of subjects as were used in the direct method (120), the number of subjects was limited to 40 (20 males and 20 females) and impedance readings were made at frequencies of 2000, 5000, 11,160 and 41,800 c./sec.

In making measurements, current was fed between electrodes A and C through a 20,000 ohm current limiting resistance and the voltage drop

[1] The phasemeters described are designed for operation at fixed frequencies. To investigate the low frequency range, special instruments would have had to be designed for each frequency investigated.

between electrodes B and A was determined by means of a vacuum tube voltmeter calibrated in ohms at each of the frequencies used.

Results. The measured impedances for these 40 subjects were found to fall on straight lines whose average slope (0·80) corresponds to a phase angle of 72°. The averages of the impedances at each frequency for all of these subjects are plotted in Fig. 6 and lie on a straight line differing but little in slope (0·79) from the average of the individual slopes.

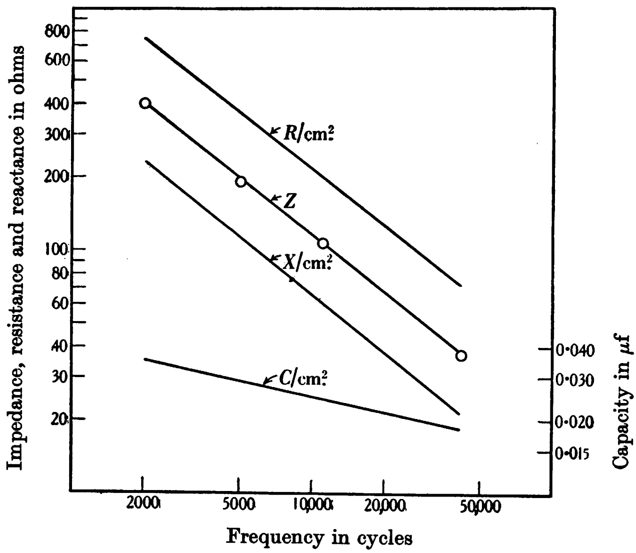


Fig. 6. Impedance components of the skin as a function of frequency. Z, average impedances of 40 subjects; electrode area 6 cm.² R, X and C, resistance, reactance and capacity per unit area of normal human skin. The curves for R and C are to scale; the X values have been divided by 10. The values of R and C are calculated for an equivalent series circuit.

The resistance, reactance and capacity of the skin per cm.², being of basic interest, have been calculated from the average normal phase angle (71·3°) and the average impedance at each frequency, and are also represented in Fig. 6. It will be noted that the slope of the capacity-frequency curve is different from that of the corresponding curves for resistance, reactance and impedance (equations (2) and (4)).

In order to verify by direct measurement the constancy of phase angle in the lower frequency range (2000–11,160 c./sec.) indicated by the linearity of the log (impedance)-log (frequency) curve, phase angle determinations were made on two subjects over the entire frequency range i.e. at 2000, 5000, 11,160 and 41,800 c./sec. Since a phasemeter operating at 2000 and 5000 c./sec. was not available for this purpose, readings were obtained at these frequencies by connecting current-carrying electrodes A and C in series with a resistance of 400 ohms, feeding the difference of potential across the resistance to one pair of plates of a cathode ray tube and simultaneously throwing the voltages tapped off between electrodes B and A across the other pair of plates; the phase angle being calculated from the form of the ellipse so produced. Phase readings made in this way were accurate to ± 3 p.c.

The phase angle values obtained for both of these subjects showed variations of less than $\pm 2°$ over the entire frequency range indicated and confirmed the constancy indicated by the linearity of the impedance-frequency curve.

The absolute value of the phase angle and its constancy with frequency as measured by the direct and indirect methods are in close agreement. The results obtained may, therefore, be taken to represent within the experimental error the average phase angle properties of normal skin over the frequency range investigated.

Comparative experimental analysis of the band, concentric and two-electrode techniques

In view of the fact that the phase angles reported here differ from those hitherto obtained (1) in remaining constant with frequency and (2) in showing values some 15–20° higher at 10,000 c./sec. than those reported by Hozawa and by Horton & van Ravenswaay, it was considered important to examine the techniques used by previous authors in order to determine wherein they were at fault.

The band-electrode method. The electrode set-up for this method described by Horton & van Ravenswaay is shown in Fig. 3*b*. As has already been pointed out, the two edges a and b of current-carrying electrode A are at a different potential with respect to voltage-tapping electrode B which is placed to one side. It would, therefore, be expected that the magnitude of the error introduced in the measurement of impedance components or phase angle would increase (1) with the width of current-carrying electrode A, (2) with the separation of electrodes A and B and (3) with the frequency.

The possibility of the measured phase angle decreasing with increased electrode width was indicated in the work of the authors of this method. Their measurements with an electrode 1·5 cm. wide at 10,000 c./sec. gave a value of 54° whereas with an electrode of twice this width (3 cm.), a phase angle of about 40° was found at the same frequency. (It is not stated whether or not these measurements were made on the same individual.) To determine the effect of varying electrode widths, a series of measurements was made of the phase angle of the skin area under electrode *A* with electrodes 2, 10 and 20 mm. wide (Fig. 3*b*), voltage-tapping electrode *B* being maintained first a fixed distance and then, at varying distances, from *A*. The 10 and 20 mm. electrodes were made of sheet tin covered with flannel and soaked in 1 p.c. saline. The 2 mm. electrode was a flattened band of solder wire without any covering,

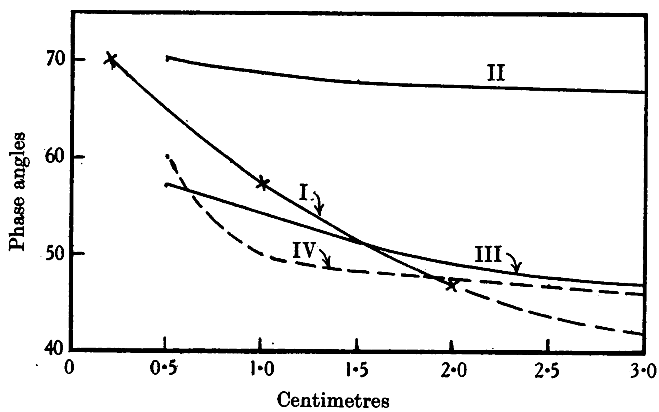


Fig. 7. Effect of electrode size, position and spacing on the measured phase angle. Curve I. Band electrode technique: effect of varying the width of current electrode *A* (Fig. 3*b*) alone; electrode *B* at a constant distance of 5 mm.; abscissæ, width of band *A*, ordinates, phase angles. Curve II. Band electrode technique: effect of varying the spacing between bands *A* and *B*; electrode *A*, 2 mm.; abscissæ, distances between electrodes, ordinates as in I. Curve III. Similar to curve II, band *A*, 10 mm. wide. Curve IV. Concentric electrode technique: effect of displacement of electrode *B* from inside to positions at various distances outside annulus *A*; abscissæ, distances from annulus, ordinates as in I. The displacements of electrode *B* were made towards the left of the position shown in Fig. 3*e*. Measurements similar to curves II and III with electrode *A* 20 mm. wide gave values below the range of the phasemeter (45°) at distances of 1 cm. or more.

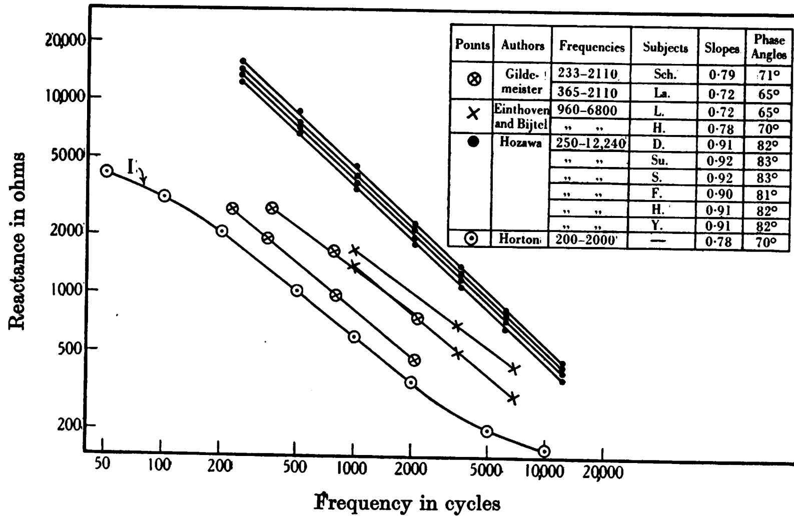
fastened over the saline moistened skin. All measurements were made at 15,300 c./sec. using the phasemeter described. The results are shown in Fig. 7.

With voltage-tapping electrode *B* at a fixed distance of 5 mm., the phase angle values diminish rapidly with increasing electrode width, dropping sharply from 70° for the 2 mm. electrode to 47° for one of 20 mm. (curve I). Attempts were made to obtain measurements with an electrode 30 mm. wide, but the phase angle fell below the range of the phasemeter which was calibrated for values between 45° and 90°. By extrapolating along curve I a value of 42° is obtained. The phase angle of the skin of this same subject measured with a concentric electrode was found to be 73°.

The effect of increasing the spacing between electrodes *A* and *B* is shown in curves II and III. The phase angle decreases with increasing electrode separations up to 30 mm., the rate of decrease being markedly less for a narrow than for a wide electrode. No significant differences in the phase angle values were noted using voltage-tapping electrodes of 2 and 10 mm. width either when the width of electrode *A* was varied alone or when the electrode separation was varied keeping the width of electrode *A* constant. It will be noted that the results obtained with a bare metal 2 mm. electrode, 70°, are closest to those for the concentric electrode (73°).

Comparative experiments were also carried out using concentric electrodes *A–B* to determine the effect (1) of varying the direction of current flow and (2) of shifting voltage tap *B* from inside to outside the annulus. The experimental set-up is shown in Fig. 3*e*. No significant difference in phase angle was obtained by shifting current electrode *C* from a position opposite electrode *A* (dotted line position) to a position 10 cm. along the arm on the same side (full line position). With electrodes *C* and *A*, in this latter position, the effect of shifting voltage-tapping electrode *B* from inside to a position 5 mm. outside annulus *A* was to drop the measured phase angle from 73° to 60° and, as electrode *B* was moved away from the periphery of the annulus, the decrease in phase angle shown in curve IV was obtained.

The effect of changes in frequency on the phase readings may be deduced from the results reported by Horton & van Ravenswaay. Using a current electrode 3 cm. wide, these authors give a reactance-frequency curve which, when plotted on log log co-ordinates as in Fig. 8, is substantially linear between 200 and 2000 c./sec. but which diminishes in slope at frequencies lying both below and above this range. From the Fricke relation, it follows that the phase angle should remain constant over the linear range. The slope of the linear portion is 0·78, giving a phase angle of 70°. This value is of the order of those found with concentric electrodes. The non-linearity of the reactance-frequency curve at low frequencies may be due to an actual change in the phase angle of the skin. At frequencies above 2000 c./sec. the non-linearity of the curve may be explained on the basis of a progressive increase in the potential gradient across the electrode. The work of Horton & van Ravenswaay indicates that the impedance of the deep tissues (inner impedance) remains substantially constant at frequencies up to 10,000 c./sec. It can be shown that, in an infinite network composed of an impedance of constant value (deep tissue) shunted by a series of condensers (the skin), the potential gradient will tend towards zero as the frequency is decreased.



Points	Authors	Frequencies	Subjects	Slopes	Phase Angles
⊗	Gildemeister	233-2110	Sch.	0·79	71°
		365-2110	La.	0·72	65°
×	Einthoven and Bijtel	960-6800	L.	0·72	65°
		" "	H.	0·78	70°
●	Hozawa	250-12,240	D.	0·91	82°
		" "	Su.	0·92	83°
		" "	S.	0·92	83°
		" "	F.	0·90	81°
		" "	H.	0·91	82°
		" "	Y.	0·91	82°
⊙	Horton	200-2000	—	0·78	70°

Fig. 8. Reactance as a function of frequency according to various authors. The curves are identified in the chart. The results for all normal subjects reported in the literature (except as indicated below) are given in which measurements were made of the skin of the *arm* at more than two frequencies. The curves for two of the subjects of Hozawa are not plotted. They fall on or across the four upper curves and have been omitted to avoid confusion. The curves omitted are also linear. Their slopes are included in the chart. The reactance values in curve I have been multiplied by 10.

The two-electrode method. The technique of Hozawa will be taken as illustrative of this method. This author uses two platinum electrodes of 4·2 cm.² area spaced at a distance of 10 cm. along the forearm, the upper electrode lying just below the bend of the elbow. It can be shown that the measurements of the impedance properties of the "skin" made in this way include a large deep tissue component. To do this, two concentric electrodes are mounted on the forearm as shown in Fig. 3*f* in the positions indicated by Hozawa. Current is fed from annulus *A* to annulus *A′* and voltages are tapped from the two centre electrodes *B*, *B′*. The impedance corresponding to this difference of potential and the phase relation between current and voltage may then be determined by means of an A.C. comparator described elsewhere [Bagno & Barnett, 1938]. The values obtained represent the properties of the deep tissues, the effect of the skin being eliminated. In six subjects measured in this way at 11,160 c./sec., the impedances varied from 102 to 190 ohms depending on the arm size and the amount of subcutaneous fat [Barnett, 1937] and the Q-factor from 0·22 to 0·08. By tapping voltages from electrode B and its corresponding annulus A instead of from B and B' (Fig. 3e, full line position) the phase angle and impedance of the skin area under the annulus may be determined without disturbing the electrodes. Finally, the phase angle of the skin and the deep tissues together may be measured by connecting annuli A and A' across the terminals of a phasemeter designed for two-electrode operation [Barnett, 1935]. In a typical instance in which the phase angle and the impedance of a 6 cm.^{2} skin area under one annulus were 71·5° and 125 ohms respectively at 11,160 c./sec., the corresponding values for the deep tissues lying between the electrodes were 6·4° and 104 ohms. The measured overall phase angle for all the anatomic elements between electrodes (skin—deep tissues—skin) was found to be 49·0° which is in good agreement with the value calculated from the impedance properties of the skin and the deep tissues taken separately (48·7°). These values are of the order of those reported by Hozawa at 12,240 c./sec. It is obvious that skin phase angle determinations made by two-electrode techniques are subject to serious error due to the impossibility of excluding the effect of deep tissues. In the particular case given, this error exceeded 20°. Since the impedance of the skin decreases with frequency (Fig. 6) while that of the deep tissues remains relatively constant [Horton & van Ravenswaay], the magnitude of the error introduced by the deep tissues should increase with frequency. It is, probably, for this reason that the phase angle-frequency curves of Hozawa, Gildemeister and Einthoven & Bijtel show a decreasing characteristic with increasing frequency. The experimental data of Gildemeister and of Einthoven & Bijtel permit an estimate of the phase angle of the skin independently of the deep tissue impedance. It will be shown further on that, by excluding this impedance, phase angles calculated from their skin data become constant with frequency and show an absolute value corresponding closely to those obtained by the concentric electrode technique.

Discussion

The measurements made here represent, strictly speaking, the properties of the "surface sheath". While the depth of this sheath has not yet been directly measured, there are reasons for believing that it represents only the epidermal layers of the skin. The impedance of blood

[Crile *et al.* 1922] and of highly vascular tissues such as muscle [Eyster *et al.* 1933] is known to be relatively low. The epidermis is substantially avascular and this would tend to make it a poor conductor. The presence of a capillary bed just beneath the epidermis (in the corium) would appear to provide a conducting sheath of low impedance forming a sharp electrical boundary for the poorly conducting surface sheath. This view is in accord with those of previous workers in this field. Gildemeister, Einthoven & Bijtel, and Hozawa interpret their measurements of the "skin" as representing the properties of the epidermis. Although only two electrode techniques were available to these authors, it was recognized by all of them that a clear distinction must be made between the properties of subepidermal structures and those of the epidermis itself. In tapping off voltages through the skin, the epidermis appears to function as a relatively high impedance layer interposed between the voltage-tapping electrode and the more highly conducting underlying structures composed of the derm proper, the subcutaneous tissues and the muscles.

It has already been shown that the linear portion of the log (reactance) log (frequency) curve of Horton & van Ravenswaay (curve I, Fig. 8) indicates the existence of a condition of constant phase angle over the range 200–2000 cycles and an absolute value of 70° within this range for the single subject measured. It was thought to be of interest to make corresponding log log plots from the reactance data of Gildemeister, Einthoven & Bijtel and Hozawa for purposes of comparison. The curves obtained are shown in Fig. 8. They have a striking common feature. All of the curves are linear over the entire range of frequencies employed. The linear slopes and corresponding phase angles (equation 4) are tabulated in Fig. 8. The four subjects of Gildemeister and of Einthoven & Bijtel show phase angles (65–71°) falling within the limits of the distribution curve in Fig. 5. Those of Hozawa run consistently higher, with a mean of 82°. There is no apparent explanation for the elevated results obtained by this author. They may, possibly, be due to the race of his subjects (Japanese).

The discrepancies between the phase angles calculated directly from resistance and capacity values at each frequency (Fig. 1) and those obtained above by use of the Fricke relation from the reactance-frequency data alone are easily explained. In the former case, the phase angle of deep tissue being small (curve VI, Fig. 1), substantially all of the deep tissue impedance is included as resistance in the calculations and introduces an error which, it has already been shown, increases with frequency.

The reactive component of the deep tissue impedance, on the contrary, is negligibly small in comparison with that of the skin. The measured reactances, therefore, represent closely the properties of the skin itself.

Analysed in this way, the data obtained by two-electrode techniques are seen to be in excellent agreement with the phase angle findings reported herein both as to constancy with frequency and, the results of Hozawa excepted, as to absolute value.

It is important to correct a systematic error which has appeared in previous work relative to the calculation of the polarization phase angle of normal human skin. The Fricke relation was published in 1932. Prior to that time, following the initiative of Wien [1896], it was customary to calculate the cotangent of the phase angle, ϕ, of a polarization impedance from the formula

$$\cot \phi = 2\pi \times (\text{frequency}) \times (\text{capacity}) \times (\Delta R), \qquad \ldots\ldots(6)$$

where ΔR represented the difference between the measured resistance and the resistance at infinite frequency. For metals dipping into solutions, the cotangent values frequently remain constant with frequency. The infinite frequency value was generally taken as the impedance measured at about 100,000 c./sec. or estimated from the intercept on the resistance axis at zero reactance of the resistance-reactance curve. Gildemeister, in 1928, using this method, found cot ϕ, calculated from his own data and that of Einthoven & Bijtel, to remain substantially constant with frequency. This constancy, it can be shown, is the result of a fortunate choice of frequency (100,000–150,000 c./sec.) for estimating the infinite frequency resistance. The deep tissues cannot properly be considered as purely or even approximately resistive at 100,000–150,000 c./sec. as in the case of solutions. Measurements by the present author above the frequency range investigated by Horton & van Ravenswaay show the phase angle of the inner impedance to increase continuously up to 126,000 c./sec. (curve VI, Fig. 1) when measured along the arm axis. Transversely through the arm (Barnett, 1937), the phase angle of deep tissue may be as much as three times the longitudinal value and has been found to have a more steeply rising frequency characteristic. It follows therefore that (1) to obtain a proper infinite frequency value for the skin itself, measurements would have to be made at millions of cycles, and (2) as higher and higher frequencies are employed, ΔR will increase continuously and cot ϕ will be less and less constant with frequency. It is probably because of the impossibility of accurately estimating the infinite frequency resistance from existing data that Cole's calculations [1933] based on the measurements of Gildemeister and of Einthoven & Bijtel give a polarization phase angle of only 55°.

Cole [1932] has made explicit reservations regarding the applicability of the network shown in Fig. 2*a* to tissues. He and Curtis [1936] have been able to show that, in the case of sheathed structures such as the sciatic nerve of the frog and the cat, at least two variable impedance elements are present, one accounting for the properties of the sheath and the other for the bundle of nerve fibres inside the latter. There is a possibility that the same is true for muscle sheaths and the muscle fibres contained therein. In the case of biological materials such as suspensions of red cells and marine eggs, where an enclosing sheath is absent, the impedance properties of all the cells are well represented up to high frequencies by a network containing a single variable impedance element of constant phase angle. This may be due to the fact that the individual cellular elements are nearly alike and widely spaced. In the case of the skin, the various cellular layers composing the epidermis are packed closely together and change progressively from a wet type in the stratum germinativum to a relatively dry type in the higher layers. The cells in the upper tiers must, obviously, differ in their electrical properties from those lower down. It might, therefore, be expected that, for the skin, one must postulate as many different variable impedance elements as there are types of cells. The experimental data here presented indicate, nevertheless, that the properties of the skin over the range 2000–40,000 c./sec. may be represented by a single bare variable impedance element of constant phase angle as shown in Fig. 2*b*. The analysis of the work of previous authors (Fig. 8) makes it probable that this simple network is valid down to about 200 c./sec. At frequencies below 200 c./sec., the measurements of Horton & van Ravenswaay appear to indicate a progressive decrease in phase angle (Fig. 8). This can be accounted for, as shown in Fig. 2*c*, by the intervention of the leakage resistance of the skin, R_1, which is known to be of the order of 75,000 ohms/cm.^{2} for most normal individuals [Einthoven & Bijtel]. The network represented in this latter figure may, therefore, be taken, provisionally, to summarize the impedance properties of the skin from zero to 40,000 c./sec.

The extreme simplicity of this network is very striking considering the heterogeneity of the cellular aggregate of which the epidermis is composed. Blinks [1933] has suggested that, in tissues where the cellular elements are non-spherical and closely packed, the possible intervention of distributed capacities such as are found in cables is to be considered. It is known that distributed networks of this kind may be arranged to give capacities varying with frequency in the same way as the single variable impedance polarization element postulated by Cole. It would seem hazardous, at the present time, to speculate as to whether the constant phase angle of the skin is due to polarization effects or distributed capacities or both. Nevertheless, as throwing possible light on an eventual choice, it may be of interest to note, that, in four different types of cases in which polarization phenomena are observed—the skin, metals dipping into solutions, cuprous oxide rectifiers and collodion-solution interfaces—a structural gradient either is known, or appears, to exist. In the case of the skin, it is the superposed strata of the epidermis. At the surface of metals in contact with solutions, the diffuse double layer is generally assumed to present such a gradient [Muller, 1933]. For cuprous oxide rectifiers, the gradient appears at the transition zone between the pure copper on one side and the pure cuprous oxide on the other [Grondahl, 1933]. Wilbrandt [1934] and Spiegel-Adolf [1937] have reported more marked polarization properties for partially dried collodion than for the completely dry membrane. The drying collodion should present a gradient due to evaporation from the surface. In the finally dried membrane, this gradient would be greatly diminished or even destroyed.

The nature of the gradient in these various cases has not yet been determined and may be different in each case. For the skin and a number of metal-solution interfaces [Fricke], the Fricke relation has been shown to hold over a certain frequency range. Mathematical analysis and experimental evidence [Muller] point to a probable exponential type of gradient both as to potential and charge distribution in the diffuse double layer. The charges of opposite sign in this layer may be treated as condensers. Methods for calculating the properties of electrical networks made up of condensers and resistances and having exponential and other types of gradients are well known. Preliminary studies of various networks with exponential gradients have been made with a view to determining whether or not a constant phase angle characteristic may be obtained. It has been found that, in an infinite network composed of a series of condensers each shunted by a resistance, if the resistances change exponentially with relation to the capacity, the phase angle at the terminals rises from zero at zero frequency to a plateau value which remains constant over a very wide frequency range. The detailed analysis of this and similar networks will be presented in a separate paper wherein the question of their possible use as a representation of the properties of the skin and other structures showing polarization phenomena will be taken up.

The problems relative to the measurement of the impedance properties of sheathed structures such as nerve trunks, nerve fibres (and possibly isolated muscle) are very analogous to those presented by the skin and the deep tissues. The phase angle of frog nerve sheath (sciatic) has been found to be 49–64° [Cole & Curtis, 1936]. In studies of nerve impedance made in the past, two electrode techniques have been used exclusively. It now appears that the measurements made represent largely the properties of the sheath, the high reactance of the latter at low and intermediate frequencies masking the low impedance properties of the nerve fibre bundle up to relatively high frequencies. Obviously, the properties of the nerve bundle and of its individual fibres are of greater interest than that of the sheath, and four electrode techniques would appear to offer a ready means for traversing the latter. It is believed that the experimental studies of the band, concentric and two-electrode methods here reported may prove of value in the critical evaluation of results already obtained and in the solution of similar impedance problems which present themselves in this related field.

SUMMARY AND CONCLUSIONS

1. An improved three-electrode technique for the measurement of the phase angle of the skin is described involving the use of a new type of direct-reading phasemeter and a special concentric electrode.

2. The phase angle of the skin in 120 normal subjects as measured with a phasemeter is found to vary between 64° and 78° at 15,300 cycles with a mean value of 71·3° and a standard deviation of 2·85°.

3. Impedance measurements over the frequency range 2000–41,800 cycles confirm the phase angle values found with a phasemeter.

4. The phase angle of the skin is shown to remain constant with frequency by direct measurement. The form of the impedance-frequency curve confirms the existence of this condition.

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